Geographic Information System

Coordinate System

Dr. Chan, Chun-Hsiang
Department of Geography
National Taiwan Normal University

Photo credit: ChatGPT

Outline

- What is a coordinate system?
- The shape of the Earth
- GCS and PCS
- Latitude and longitude
- Great Circle
- Projection
- Common map projections
- TWD67TM2 and TWD97TM2
- What is vector data?
- Shapefile structure

What is coordinate system?

- Before we answer this question, we have to first think about the reason why we need coordinate system?
- Imagine that you live in a world without any coordinate system, what will happen?

What is coordinate system?

- While you drive a jet in the sea, … how can you know the direction?

Source: https://eia-international.org/ocean/the-state-of-the-ocean/

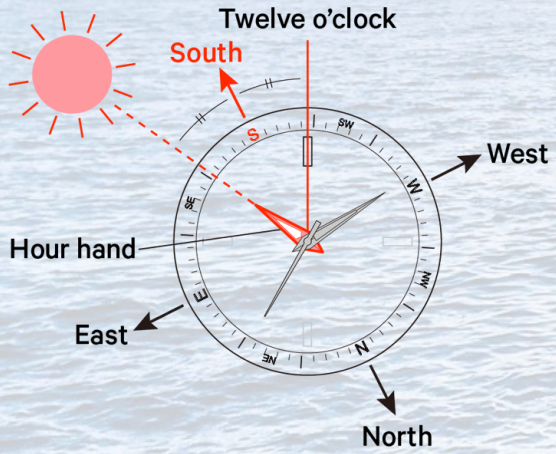
What is coordinate system?

- Find a tree?... to observe the growth (annual) rings?

Source: https://zh.wikipedia.org/zh-tw/%E5%B9%B4%E8%BD%AE#/media/File:D%C3%BClmen,_Hausd%C3%BClmen,_Baumwurzel_--_2021_--_7057.jpg
Source: https://eia-international.org/ocean/the-state-of-the-ocean/

What is coordinate system?

- How about using a watch?



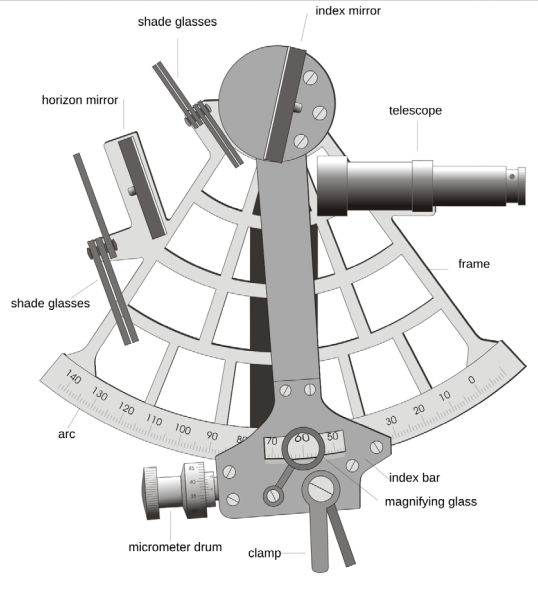
Keep in mind that these determinations are approximate as discrepancies can arise at different latitudes and in different seasons.

1. Check that the watch is showing the correct time. Then, lay the watch horizontally and align the hour hand with the direction of the sun.
2. The point approximately mid-way between the 12 o'clock position on the dial and the direction of the hour hand when it is aligned with the sun indicates south. Morning is on the left side of the dial, and afternoon is on the right side facing south.

Source: https://www.citizenwatch-global.com/support/exterior/direction.html
Source: https://eia-international.org/ocean/the-state-of-the-ocean/

What is coordinate system?

- But in the night?... using a sextant?



A sextant is a doubly reflecting navigation instrument that measures the angular distance between two visible objects. The primary use of a sextant is to measure the angle between an astronomical object and the horizon for the purposes of celestial navigation.

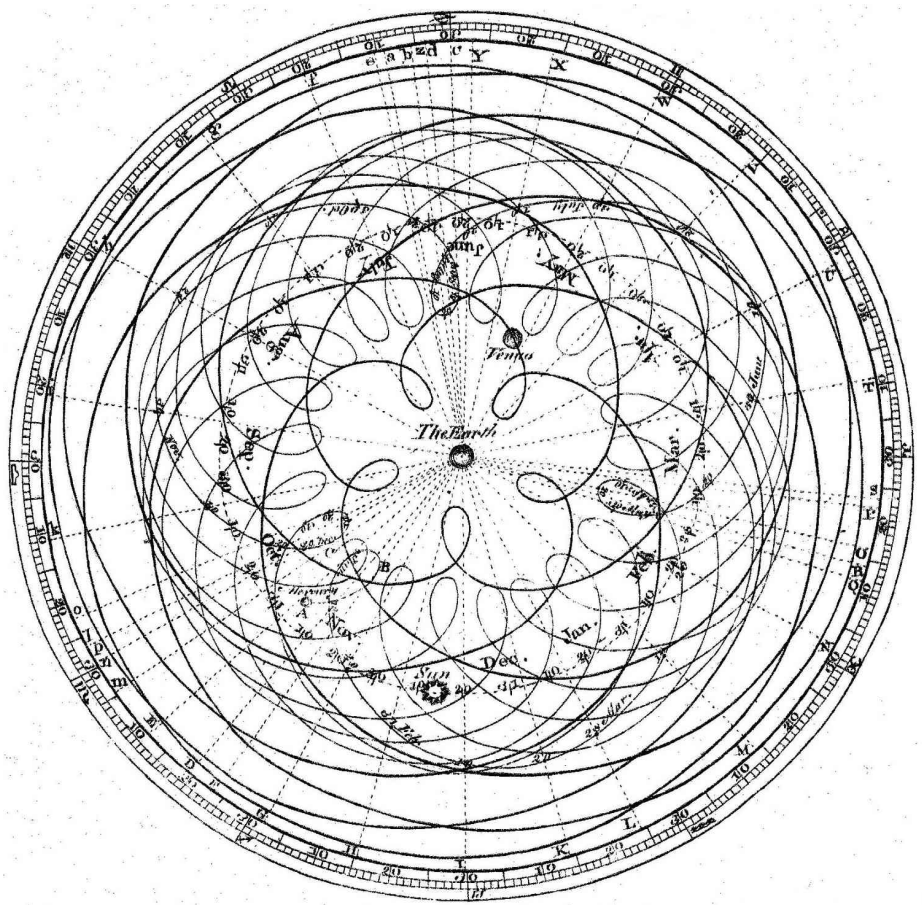
Source: https://chinese.alibaba.com/product-detail/Brass-Sextant-navigation-Sextant-marine-navigation-11000009811885.html
Source: https://en.wikipedia.org/wiki/Sextantv
Source: https://motionbgs.com/ocean-at-night

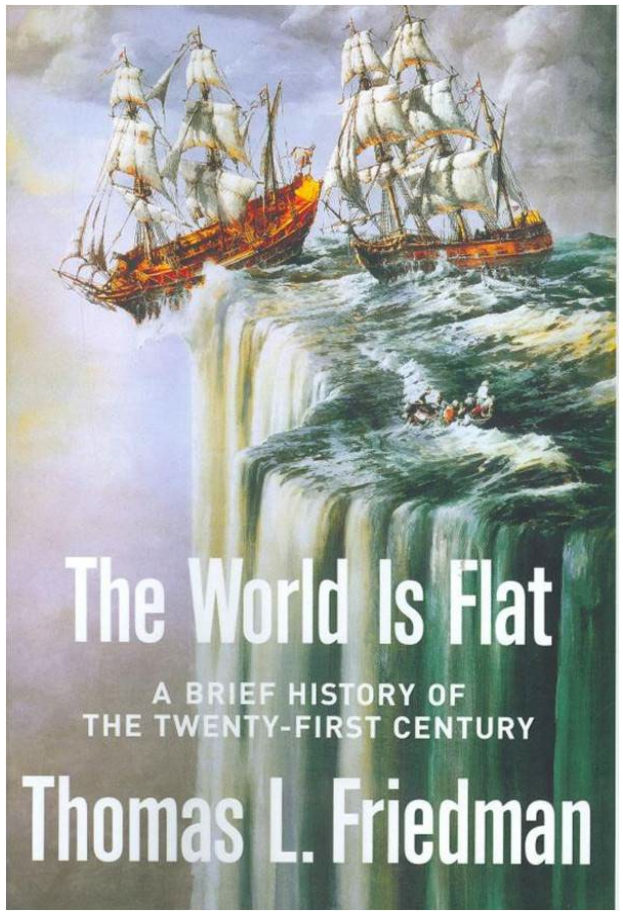
What is coordinate system?

- Why not using a map? A map that means …

Source: https://www.bbc.com/ukchina/trad/vert-tra-45373031
Source: https://eia-international.org/ocean/the-state-of-the-ocean/

What is coordinate system?

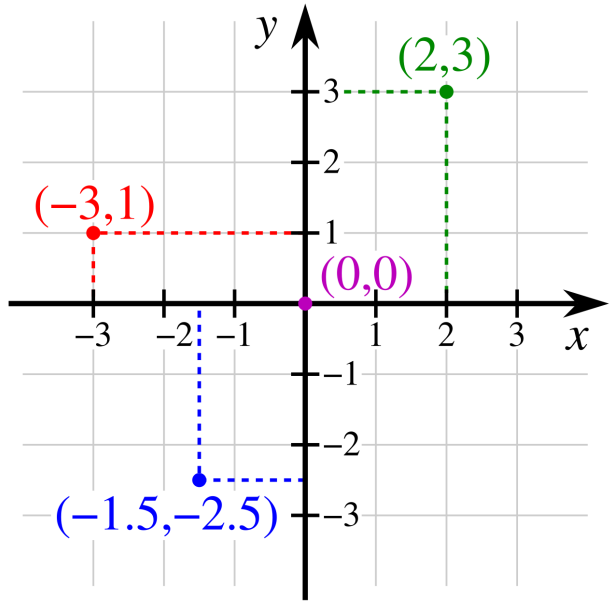


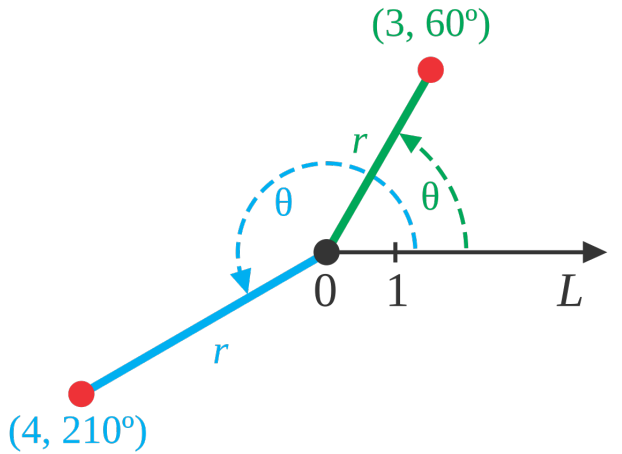


Source: https://greatescapesindia.wordpress.com/2010/03/29/the-world-is-flat-by-thomas-l-friedman-a-must-read-if-you-havent-visited-india/
Source: https://www.thoughtco.com/claudius-ptolemy-3071076

What is coordinate system?

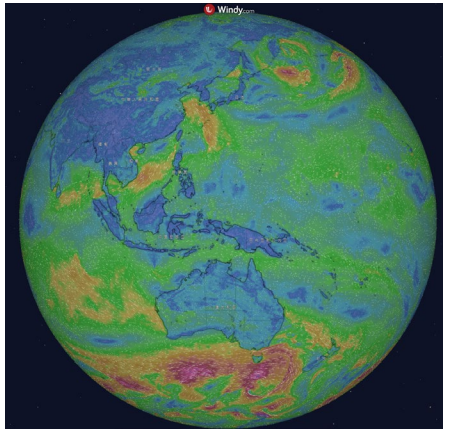
- So, if we want to draw a map, and then …
- First, we need a coordinate system to describe the distance from point A to point B. Otherwise, how can we correctly place the points, lines, and polygons on the map?
- When you were a junior high or high school student, you could draw any geometry item on a paper because you knew it followed a Cartesian or polar coordinate system.

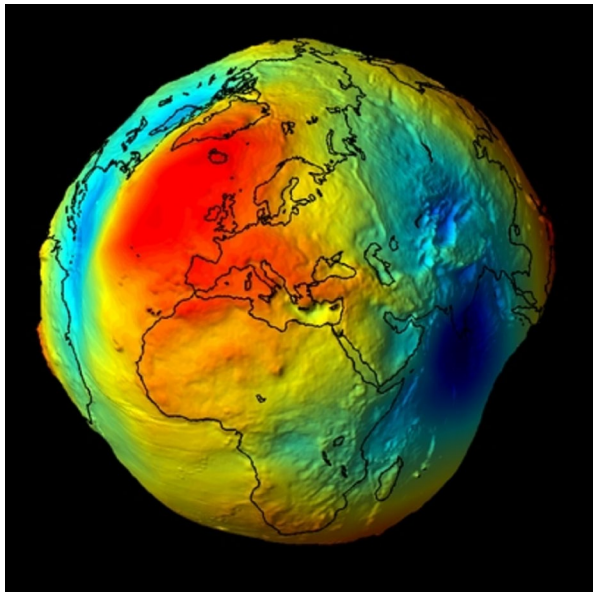




What is coordinate system?

- When you need to plot a map, what kinds of coordinate systems do you have? Or, more specifically, what kinds of coordinate systems should you use in a specific case?
- So, we need to take a look at our mother Earth…





Source: https://www.vedfolnir.com/life/finance/new-taiwan-dollars/
Source: https://www.esa.int/ESA_Multimedia/Images/2010/04/Earth_Explorers_The_Earth_s_true_shape

What is coordinate system?

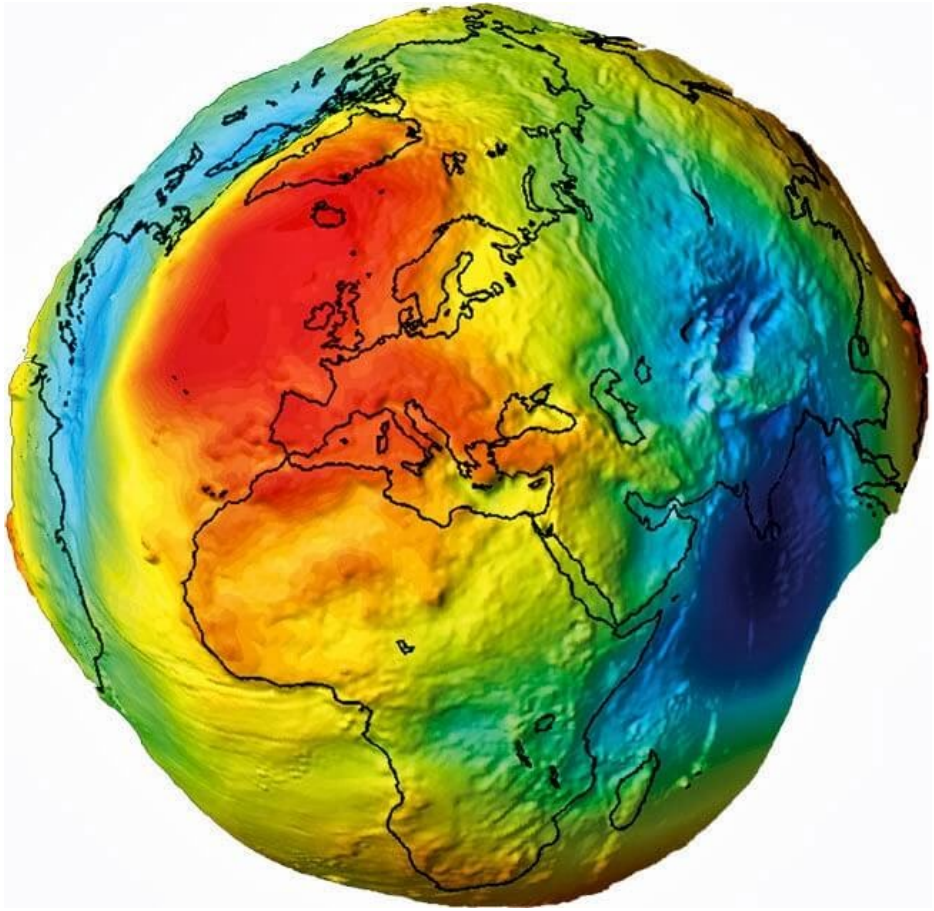
- The Earth is not a perfect sphere; it is an oblate spheroid. This means that, due to its rotation, it is slightly flattened at the poles and bulges at the equator.
- **Equatorial Bulge:** The Earth's rotation causes a centrifugal force, which pushes matter outward more strongly at the equator. As a result, the diameter at the equator is about 43 kilometers (27 miles) greater than the diameter at the poles.

The shape of the Earth

- **Flattened Poles:** The poles are slightly flattened because the Earth’s material is pulled inward due to gravitational forces.
- This shape is why the Earth's equatorial radius is about 6,378 kilometers (3,963 miles), while the polar radius is about 6,357 kilometers (3,950 miles). This difference makes the Earth an oblate spheroid rather than a perfect sphere.

The shape of the Earth

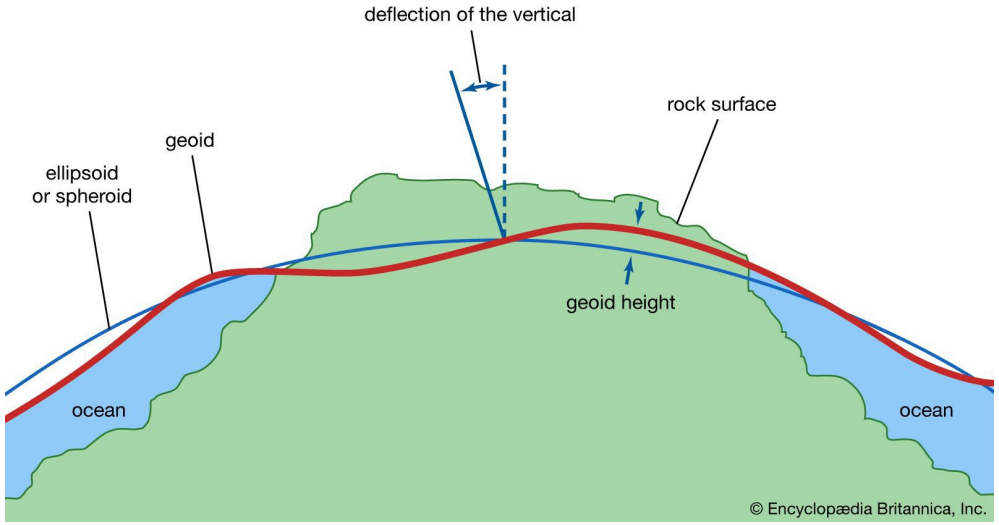
- The **geoid** (大地水準面), which is measured based on the gravity of physical geodesy (大地測量學), can closely describe the shape of the earth.
- Geodesy is the science of accurately measuring and understanding the Earth's **geometric shape**, **orientation in space**, and **gravity field** (from NOAA).



Source: https://www.iag-aig.org/doc/5cb5b3660b6c4.pdf

The shape of the Earth – Geoid

- A geoid is an **irregular-shaped "ball"** that scientists use to more accurately calculate the depths of earthquakes or any other deep object beneath the earth's surface.
- If Earth were a perfect sphere, calculations of depth and distances would be easy because we know the equations for those calculations on a sphere.



Source: https://www.usgs.gov/faqs/what-a-geoid-why-do-we-use-it-and-where-does-its-shape-come#:~:text=The%20geoid%20is%20an%20imaginary,extends%20through%20the%20land%20masses.
https://www.britannica.com/science/geoid

The shape of the Earth – Geoid

- However, the Earth more closely approximates an ellipsoid, which is what a ball looks like if you sit on it. **Ellipsoid calculations aren't as easy as spherical calculations, but they're still well-known and do-able.** Be that as it may, we all know that the earth is not really an ellipsoid because there are oceans, and mountains, and valleys, and many other features that are not part of an ellipsoid.
- **The geoid is an imaginary sea level surface that undulates (has a wavy surface) over all of the earth**; it isn't just for the oceanic areas, it also extends through the land masses.

Source: https://www.usgs.gov/faqs/what-a-geoid-why-do-we-use-it-and-where-does-its-shape-come#:~:text=The%20geoid%20is%20an%20imaginary,extends%20through%20the%20land%20masses.
https://www.britannica.com/science/geoid

The shape of the Earth – Taiwan Geoid

- The Kaohsiung Tide Station was first established in 1903, and the Keelung Tide Station was established in 1904. The Keelung Tide Station was later determined to be the Origin of Taiwan's Vertical datum.
- In 2001, the Ministry of the Interior established the Origin of Taiwan benchmark as the reference for the vertical control point system. Based on this, first-order leveling was implemented.

Source: https://www.nlsc.gov.tw/en/cp.aspx?n=2125
Source: https://zh.wikipedia.org/zh-tw/%E8%87%BA%E7%81%A3%E6%B0%B4%E6%BA%96%E5%8E%9F%E9%BB%9E#/media/File:Taiwan_datum_benchmark.jpg

The shape of the Earth – Taiwan Geoid

- The dual origin design was adopted.
  - One is the main point (point number: K999) , which is underground.
  - The other is the secondary point (point number: K998), which is a ground-surface point.
  - Both are located in Haimen Park in Keelung City; the orthometric height was adopted for the height system of the origins, with the mean sea level of Keelung Tide Station as the reference to determine Taiwan Vertical Datum 2001 (TWVD2001).
- In 2014, the Taiwan Origin benchmark was moved to the park opposite the National Museum of Marine Science and Technology with the same dual origins design, where the main point (point number: K997) is underground, and the secondary point (point number: K996) is a ground-surface point.

Source: https://www.nlsc.gov.tw/en/cp.aspx?n=2125
Source: https://zh.wikipedia.org/zh-tw/%E8%87%BA%E7%81%A3%E6%B0%B4%E6%BA%96%E5%8E%9F%E9%BB%9E#/media/File:Taiwan_datum_benchmark.jpg

The shape of the Earth – Approximation

- **How to approximate the shape of the Earth?**
  - Real Earth – irregular shape
  - Geoid surface (for measurement)
  - Spheroid (large-scale map with a high precision) ➔ WGS84
  - Referenced ellipsoid
  - Sphere
  - Authalic sphere (small-scale map with a low precision)

GCS and PCS

- Basically, we can divide all coordinate systems into two types: **Geographic coordinate system (GCS)** and **Projected coordinate system (PCS)**

  Geographic coordinate system (GCS)

  - A GCS represents locations on the curved surface of the Earth using a three-dimensional, spherical, or ellipsoidal model.
  - Coordinates are given as latitude (north-south position) and longitude (east-west position), typically measured in degrees.
  - The Earth is modeled as a spheroid or ellipsoid to account for its slightly flattened shape.

GCS and PCS

Projected coordinate system (PCS)

- A PCS is a two-dimensional, flat representation of the Earth’s surface, created by projecting the Earth's curved surface onto a flat plane.
- Coordinates are given in linear units like meters or feet, based on a Cartesian grid (x and y axes).
- Various projection methods (e.g., Mercator, UTM, Lambert) are used to transform the curved surface of the Earth into a flat map.

GCS and PCS

Curved versus Flat Surface

- The **GCS** represents locations on the **Earth's curved surface**. Since the Earth is not flat, GCS reflects this curvature.
- The **PCS flattens the Earth's surface for mapping**, which is useful for calculations and for creating maps on flat surfaces (e.g., paper or screens).

GCS and PCS

Units of Measurement

- It uses **angular units** (degrees, minutes, and seconds) to measure positions on Earth. Latitude and longitude are the standard coordinates.
- It uses **linear units** (meters, feet, etc.) to measure distances on a flat map. The x-coordinate (easting) and y-coordinate (northing) define locations in a grid system.

GCS and PCS

Accuracy and Use Cases

- GCS is **better for global positioning** because it considers the Earth's curvature. It is used in systems like GPS and is ideal for applications where global scale and precise positioning are needed (e.g., satellite navigation, global datasets).
- PCS is **better for local or regional mapping** because it projects part of the Earth's surface onto a flat plane, which makes it easier to measure distances, areas, and perform spatial analyses. However, depending on the projection, distortions in shape, area, distance, or direction may occur.

GCS and PCS

Distortion

- **GCS does not have distortion** since it represents the Earth as a 3D ellipsoid.
- **PCS's distortion is inevitable** because the process of projecting a 3D surface onto a 2D plane results in distortions in either shape, area, distance, or direction. Different projections minimize different types of distortion based on the map's purpose.

GCS and PCS

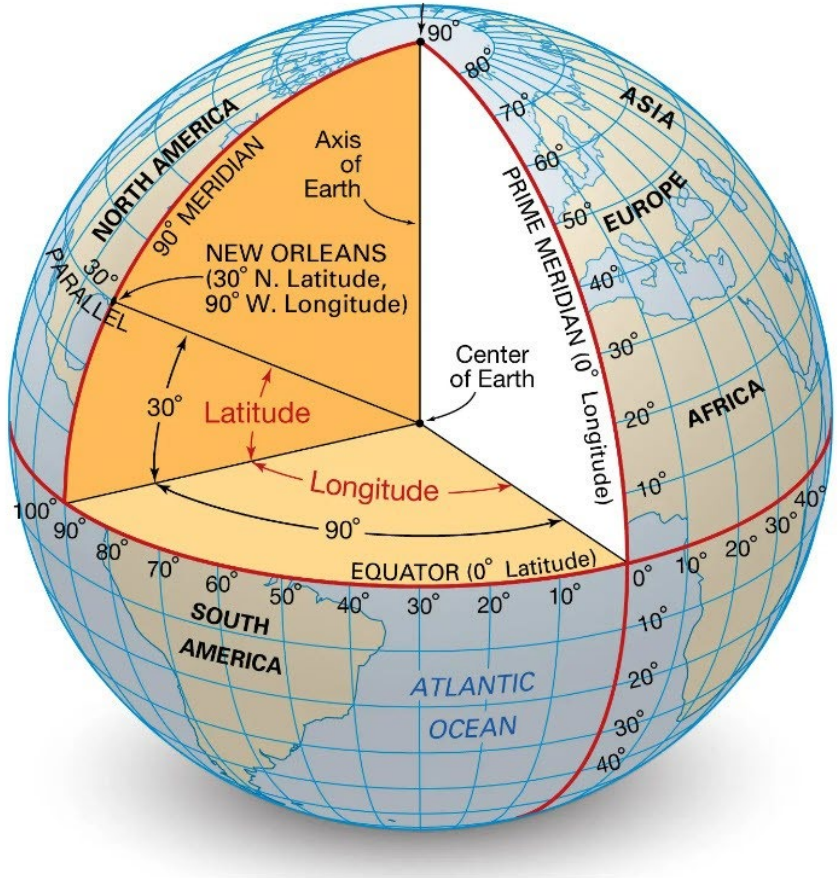
Lab Practice #01

- Search the following:
  - TWD97TM2 Taiwan
  - TWD67TM2 Taiwan
  - WGS84
- Record their units, suitable areas, and mark them as GCS or PCS

Latitude and longitude

Latitude

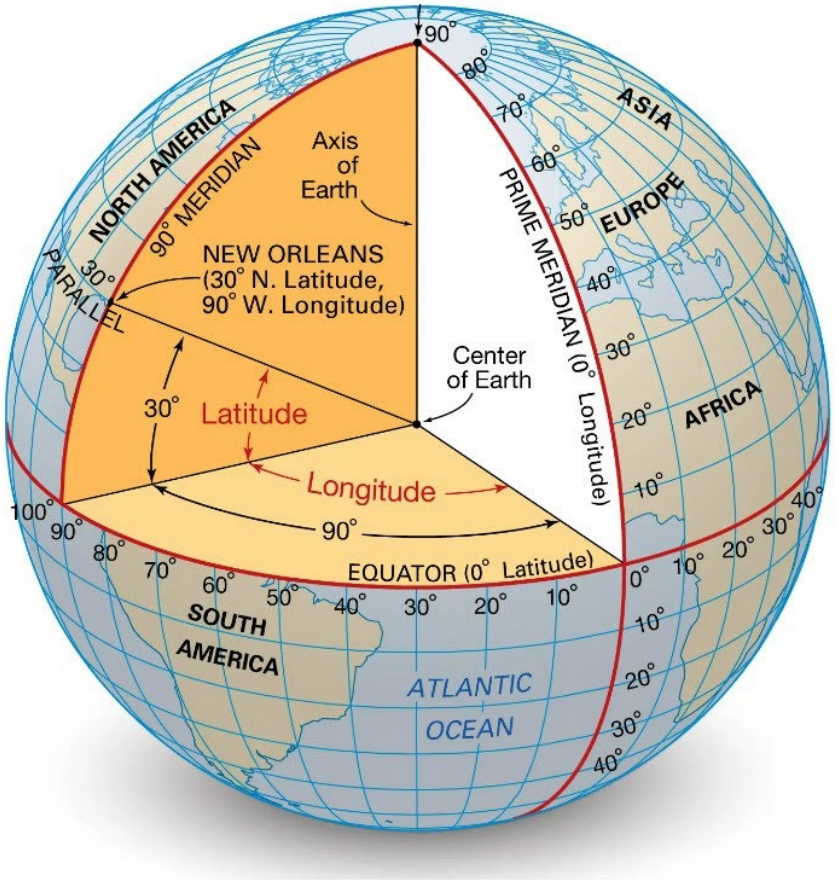
- **Equator:** 0° latitude divides the Earth into the Northern and Southern Hemispheres.
- Locations north of the equator have positive values (from 0° to 90° North), and locations south of the equator have negative values (from 0° to 90° South).
- Each distance between two latitudes is equal and approximates 111.2km based on the WGS84 Authalic Sphere.



Latitude and longitude

Lab Practice #02

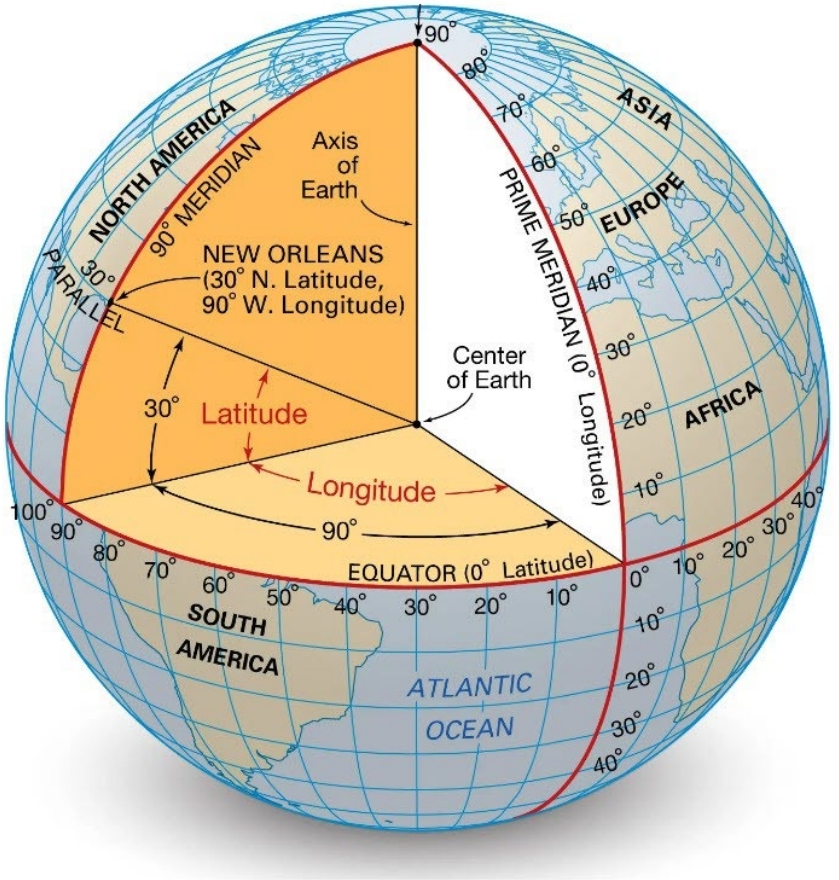
- Given the radius of the Earth (6378km), how can you prove the distance between two latitudes?



Latitude and longitude

Longitude

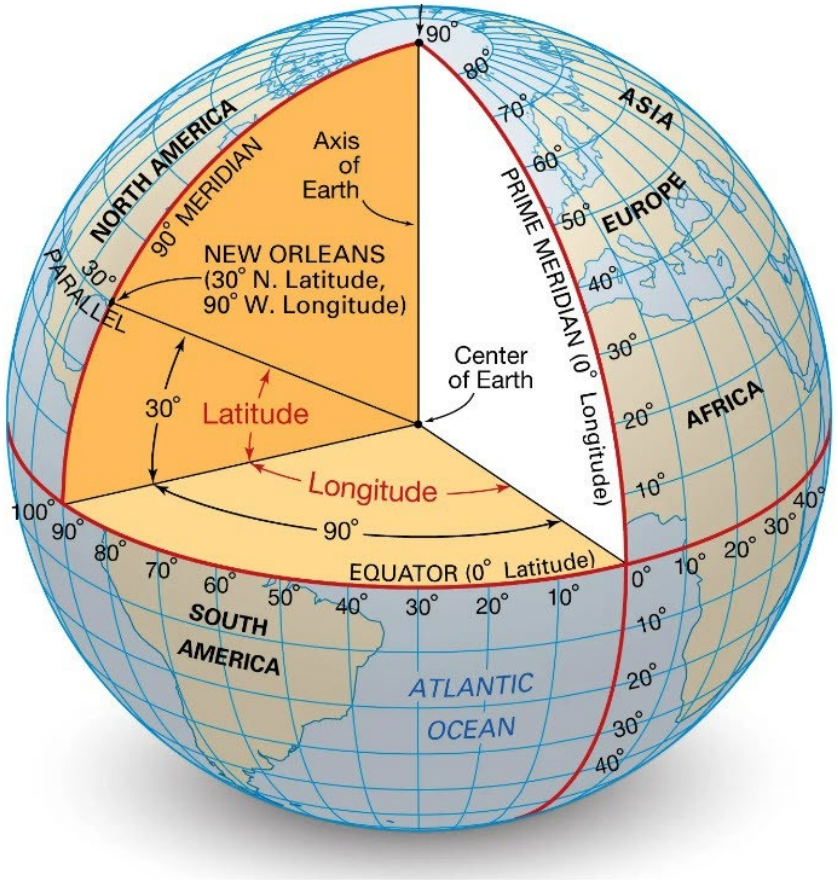
- Longitude is measured in degrees (°), ranging from 0° at the Prime Meridian (which runs through Greenwich, England) to 180° east or 180° west.
- Locations east of the Prime Meridian are measured as positive values (from 0° to 180° East), while locations west of the Prime Meridian are measured as negative values (from 0° to 180° West).



Latitude and longitude

Longitude

- Longitude is closely related to time zones. Each 15° of longitude typically represents one hour's difference in time.
- The Prime Meridian (0° longitude) is the reference for Coordinated Universal Time (UTC).

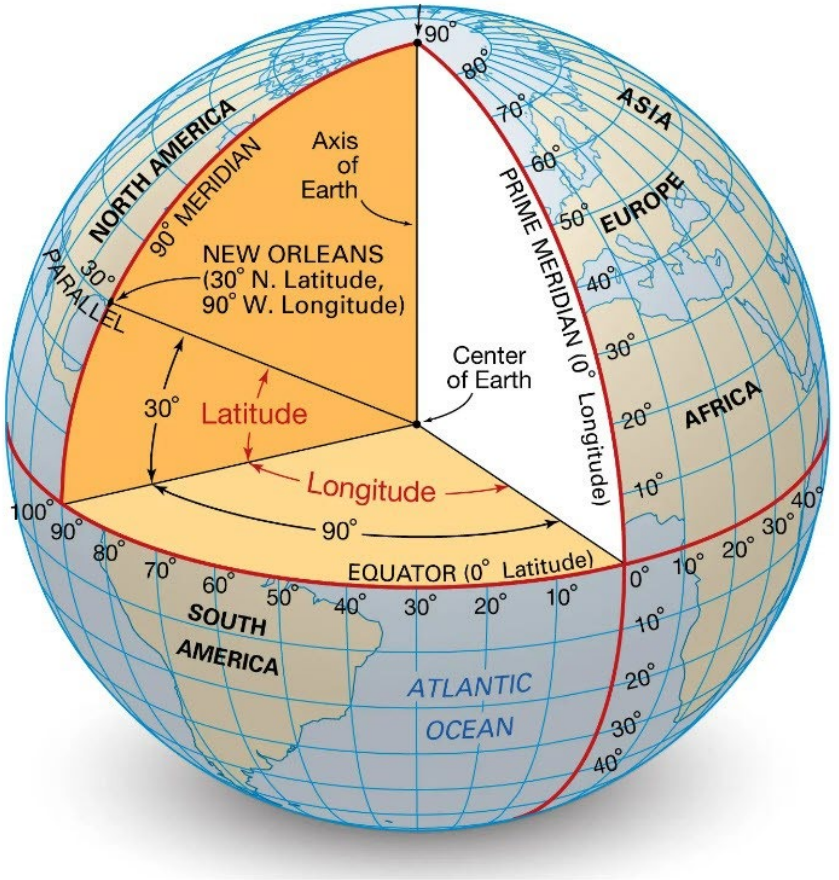


Latitude and longitude

Lab Practice #03

- What are the characteristics of latitude and longitude?

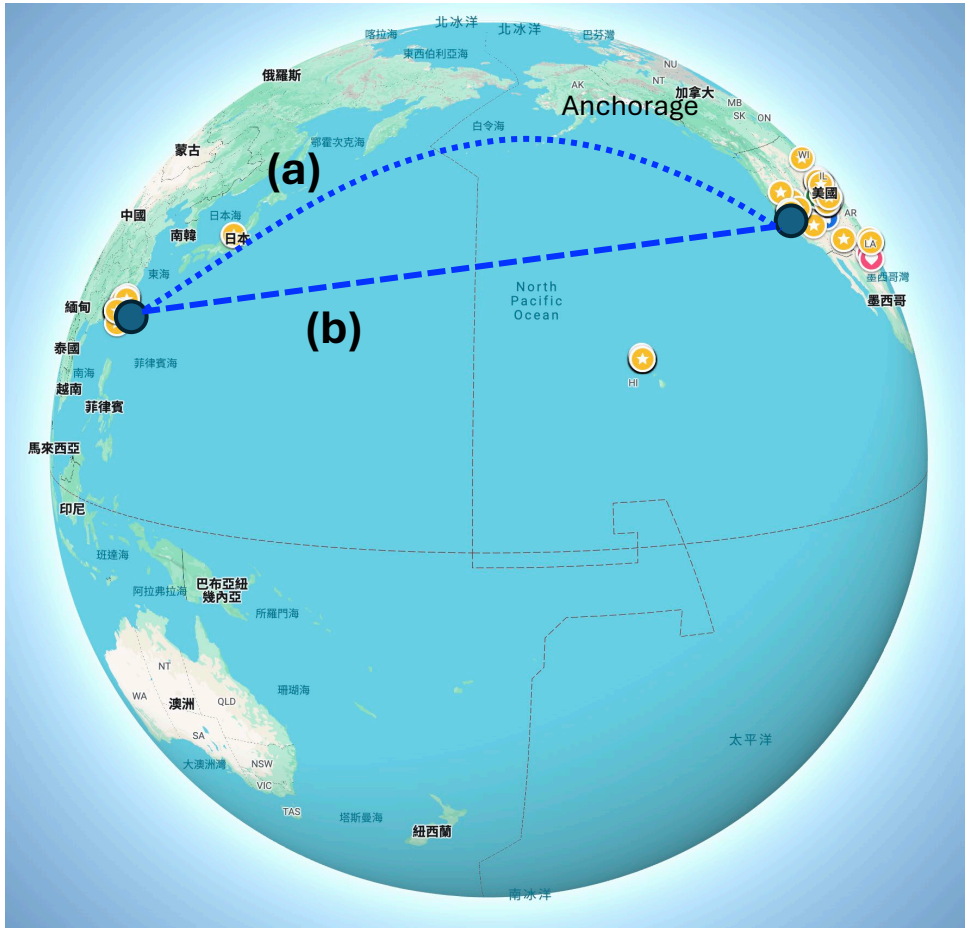
- Where is the origin point? On the sea? Or is it located in a specific country?



Great Circle

Great Circle

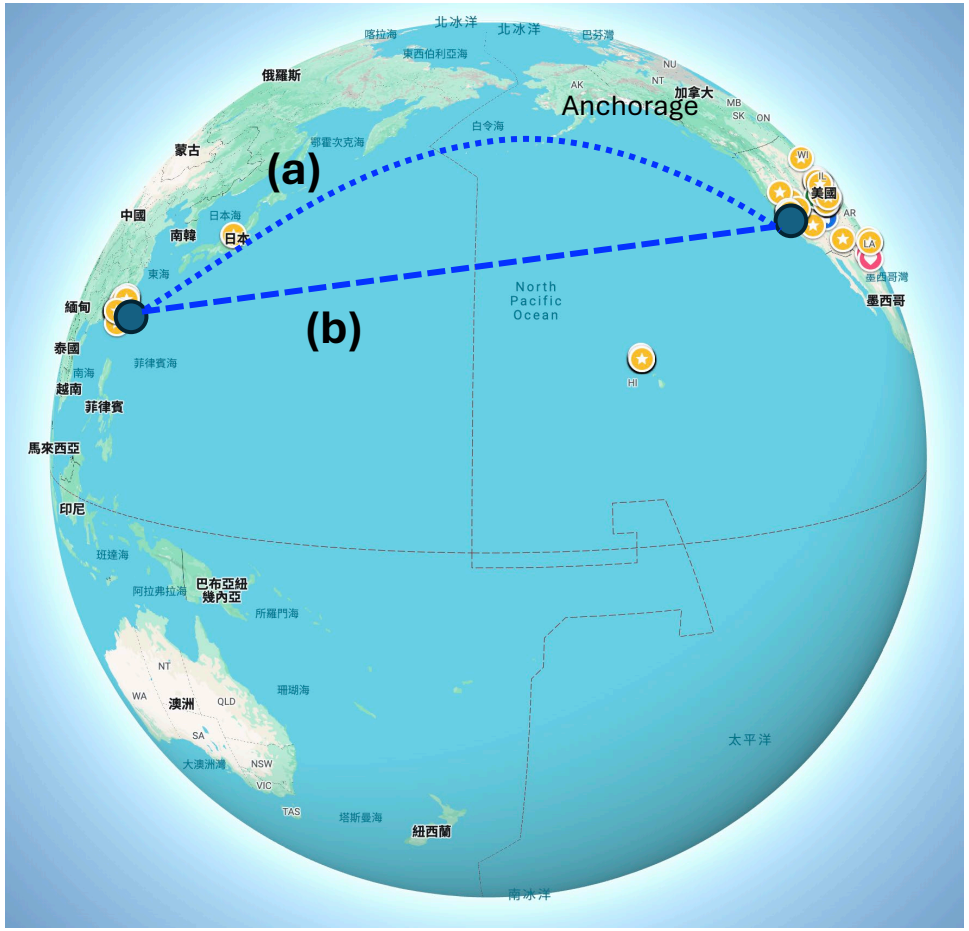
- A great circle is the largest possible circle that can be drawn on a sphere, and it represents the shortest path between two points on the surface of that sphere. On Earth, a great circle is any circle that divides the planet into two equal halves.



Great Circle

Great Circle

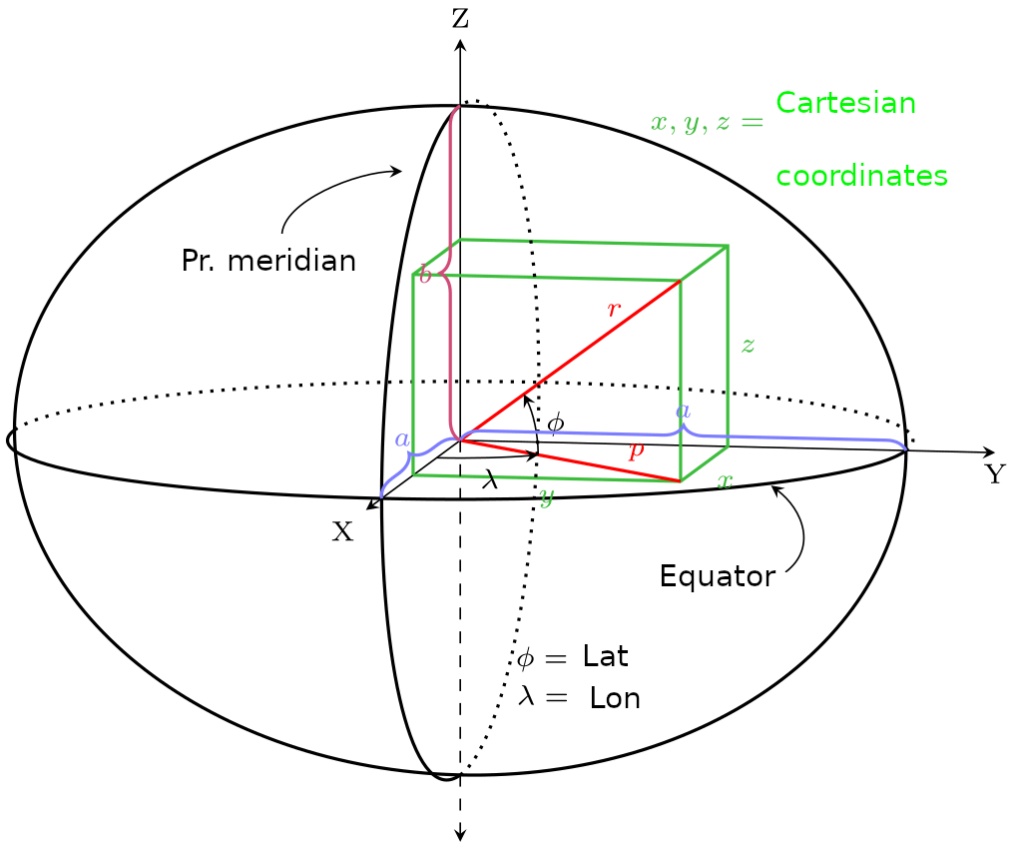
- A great circle is a circle on the surface of a sphere whose plane passes through the center of the sphere.
- The arc of a great circle, also known as a geodesic, is the shortest distance between two points on Earth. For long-distance flights, airplanes often follow great circle routes to minimize distance and fuel consumption.



GCS and PCS

Using the Ellipsoid as a referencing standard, …

- Ellipsoid is the real shape of the Earth; therefore, a coordinate system usually refers to ellipsoid.
- Latitude and longitude can still follow the abovementioned context, i.e., we have geodetic latitude and geodetic longitude.



Projection

- After we can identify and locate the object on the map, we want to know how to measure or calculate the area of a certain country, city, district, or building on the map.
- As you can see, how can we calculate the area of Australia?

Projection

- To correctly calculate the area and distance, we need a projected coordinate system – **Projection**.
- A map projection is a method for representing the three-dimensional curved surface of the Earth on a two-dimensional flat surface, such as a map. Since the Earth is spherical (or, more precisely, an oblate spheroid), it cannot be perfectly flattened without introducing some form of distortion.
- Map projections aim to translate geographic coordinates (latitude and longitude) onto a flat surface while managing different types of distortions.

Projection

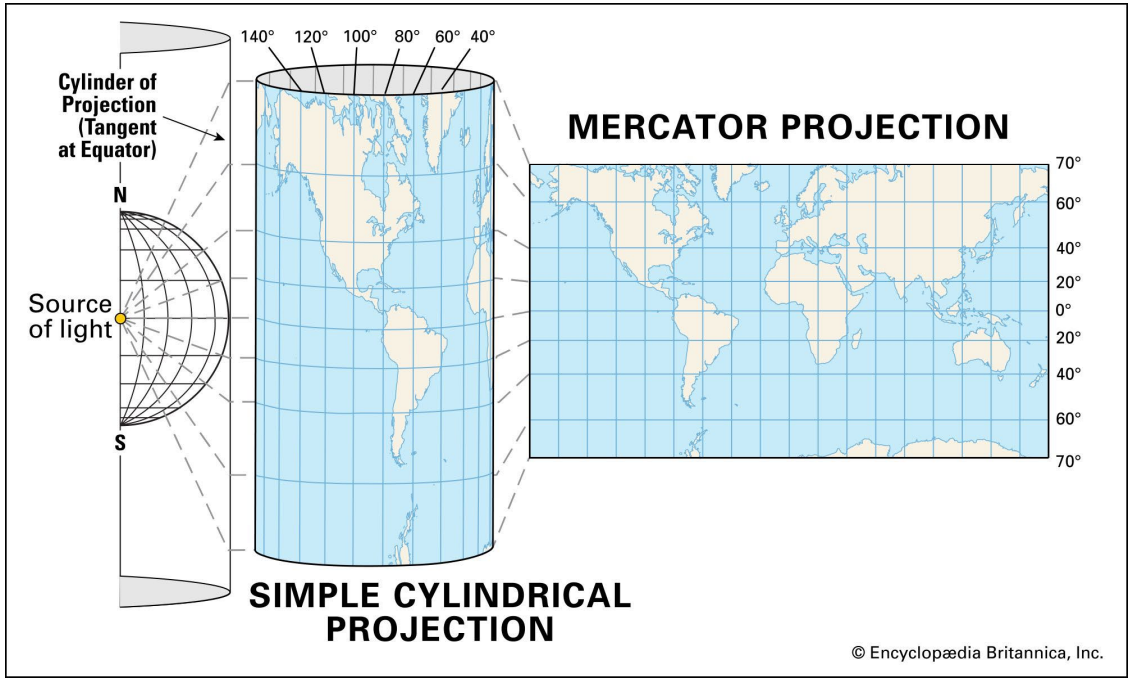
- **Types of Distortion**
  Since projecting a sphere onto a flat surface is impossible without some trade-offs, every map projection introduces distortions in one or more of the following aspects:
- **Shape (Conformal projection):** for a small region, similar shape, but enlarged area in the high latitude area.
- **Area (Equal-area projection):** fixed area ratio
- **Distance (Equidistant projection):** fixed distance followed by a specific direction
- **Direction (Azimuthal projection):** the directions from projected point to all points are fixed

Common map projections

Common Types of Map Projections: Different projections are designed to minimize certain types of distortion depending on the map's purpose:

Mercator Projection:

- **Purpose:** It preserves angles and directions, making it useful for navigation.
- **Distortion:** Distorts area, especially near the poles, making regions like Greenland appear much larger than they are.

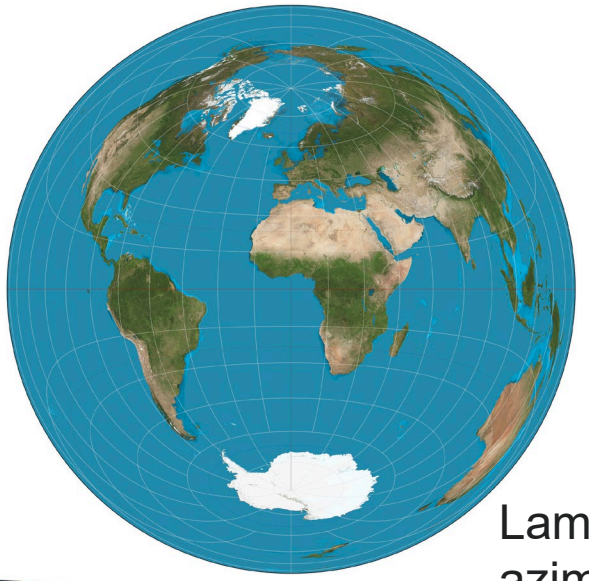


Source: https://www.britannica.com/science/Mercator-projection

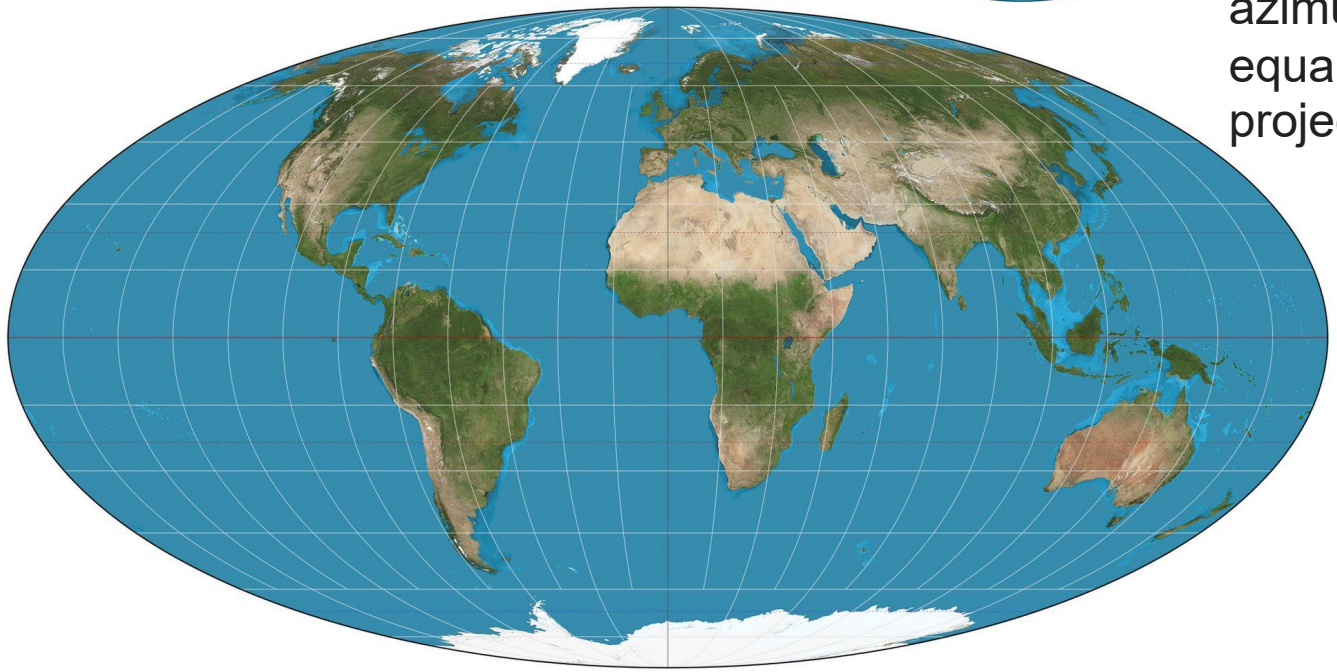
Common map projections

Equal-Area Projection (e.g., Mollweide, Albers):

- **Purpose:** Preserves area, ensuring that regions on the map have sizes proportional to their actual sizes on Earth.
- **Distortion:** Shapes are distorted, especially near the edges of the map.



Lambert azimuthal equal-area projection



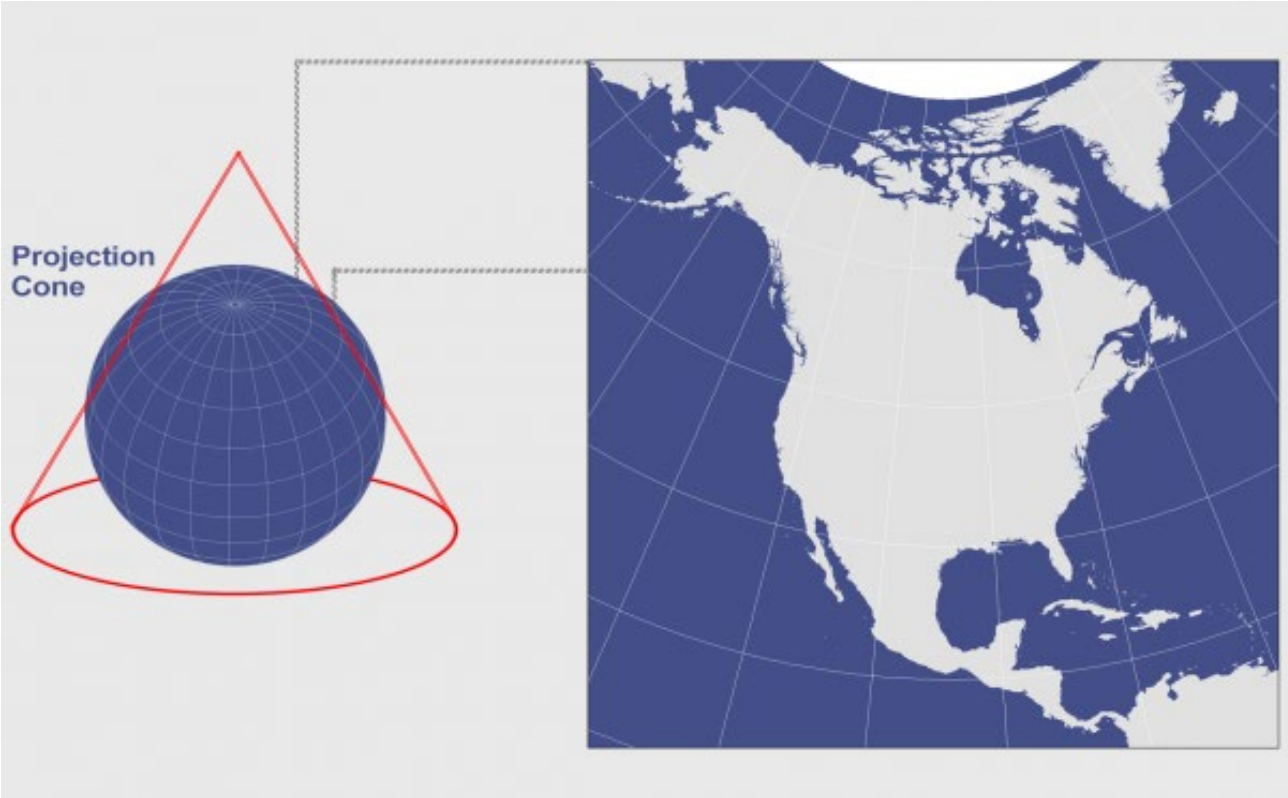
The equal-area Mollweide projection

Source: https://en.wikipedia.org/wiki/Equal-area_projection

Common map projections

Conic Projection (e.g., Lambert Conformal Conic):

- **Purpose:** Often used for mid-latitude regions (like the U.S.), useful for regional mapping.
- **Distortion:** Minimizes distortion along certain parallels but distorts areas farther from the "standard parallels.“

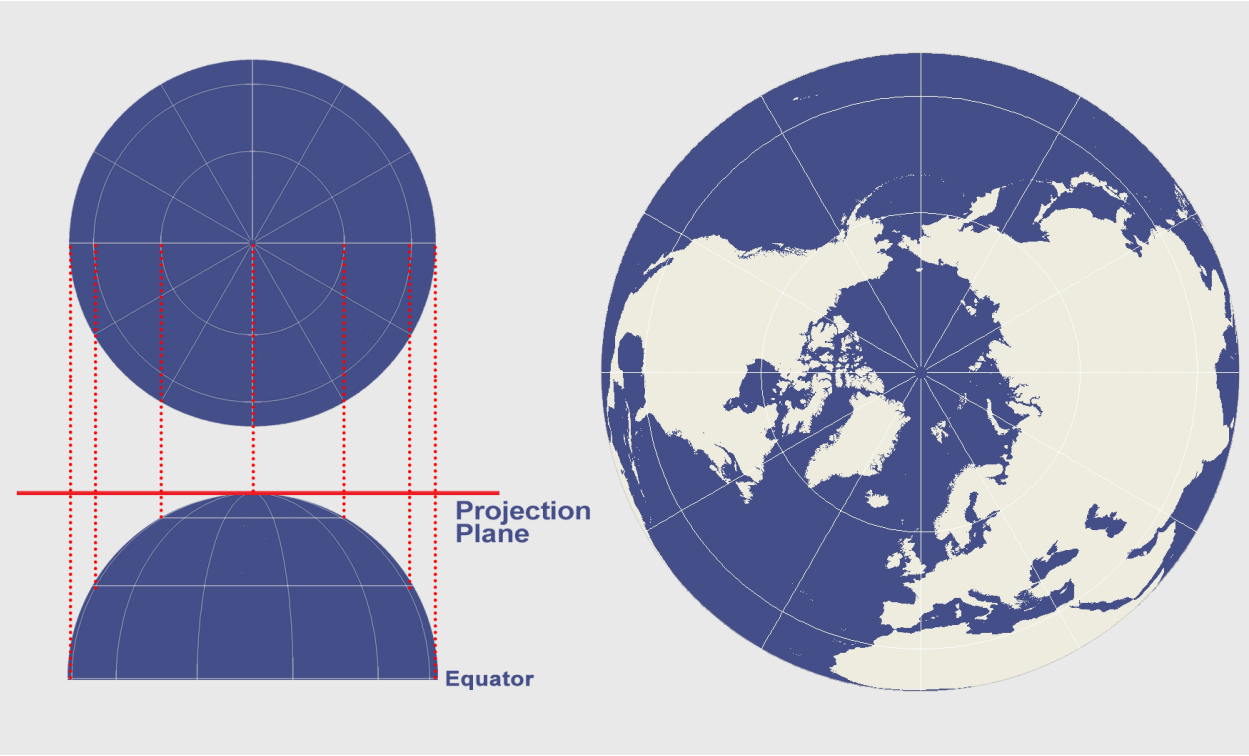


Source: https://gisgeography.com/conic-projection-lambert-albers-polyconic/

Common map projections

Azimuthal Projection (Stereographic or Orthographic):

- **Purpose:** Represents the Earth as seen from a specific point, often used for polar regions.
- **Distortion:** Distorts shape and distance as you move away from the center point.



Source: https://gisgeography.com/azimuthal-projection-orthographic-stereographic-gnomonic/

TWD67TM2

- **TWD67** (Taiwan Datum 1967) is a geodetic datum used as a reference for geographic coordinates in Taiwan. It defines the coordinate system and provides a frame of reference for mapping and spatial data within Taiwan.
- **Internal Affairs:** In 1976, the triangular point test was completed, and the "Taiwan Territory of the Republic of China" was announced.
- "**District Triangular Point Results Table**", the measurement origin is the first-class triangular point located in Huzi Mountain, Puli Town, Nantou County.

Source: https://gisgeography.com/azimuthal-projection-orthographic-stereographic-gnomonic/

TWD97TM2

- **Internal Affairs:** Since 1982, GPS satellite positioning and measurement technology has been used to manage satellite tracking stations and first — and second-class satellite control measurements to establish a new coordinate system structure in Taiwan.
- Based on the International Terrestrial Reference Frame, ITRF for short) ITRF 94 in 1997.0, 8 in the Bay Area GPS station coordinates are the basis for coordinate calculation.
- After adjustment calculations, the new national coordinate system was announced in 1997 (TWD97).

What is vector data?

- **Points:** Represent discrete locations or entities (e.g., cities, landmarks). Each point is defined by a single coordinate pair (x, y).
- **Lines (or Polylines):** Represent linear features (e.g., roads, rivers). Lines are composed of a series of connected points, forming a path.
- **Polygons:** Represent areas with defined boundaries (e.g., lakes, countries). Polygons are created by connecting a series of points into a closed loop.

What is vector data?

- **Shapefile (.shp, .shx, .dbf):** A popular format for storing vector data, used in various GIS applications.

	U_ID	CODEBASE	CODE1	CODE2	TOWN_ID	TOWN	COUNTY_ID	COUNTY	X	Y	AREA	geometry	教育程度總人數_平均
0	1463	A0901-0002-00	A0901-01-001	A0901-01	10009010	斗六市	10009	雲林縣	206196.36387	2.627961e+06	485425.94916	POLYGON Z ((206241.682 2628483.577 0.000, 2062...	11.600000
1	1677	A0901-0006-00	A0901-01-001	A0901-01	10009010	斗六市	10009	雲林縣	205739.10374	2.627403e+06	439831.86668	POLYGON Z ((205714.898 2627813.216 0.000, 2060...	11.477273
2	1453	A0901-0001-00	A0901-01-002	A0901-01	10009010	斗六市	10009	雲林縣	205813.74831	2.628280e+06	207741.13737	POLYGON Z ((205405.940 2628307.342 0.000, 2054...	16.666667
3	1605	A0901-0003-00	A0901-01-002	A0901-01	10009010	斗六市	10009	雲林縣	205374.59478	2.627949e+06	25643.79330	POLYGON Z ((205485.123 2627975.486 0.000, 2053...	11.212121

What is vector data?

- **GeoJSON:** A format for encoding a variety of geographic data structures using JavaScript Object Notation (JSON).

```
{
  "type": "Feature",
  "geometry": {
        "type": "Point",
        "coordinates": [121.23, 23.5] },
  "properties": {
        "name": "Dinagat Islands" }
}
```

What is vector data?

- **KML (Keyhole Markup Language)** is a format for representing geographic data in XML, commonly used with Google Earth.

```
<?xml version="1.0" encoding="UTF-8"?>
<kml xmlns="http://www.opengis.net/kml/2.2">
<Document>
<Placemark>
        <name>New York City</name>
        <description>New York City</description>
        <Point>
                <coordinates>-
                74.006393,40.714172,0
                </coordinates>
        </Point>
</Placemark>
</Document>
</kml>
```

What is vector data?

- **GML (Geography Markup Language):** An XML-based format for expressing geographical features.

```
<gml:Point gml:id="p21" srsName="http://www.opengis.net/def/crs/EPSG/0/4326">
<gml:coordinates>45.67, 88.56</gml:coordinates> </gml:Point>

<gml:LineString gml:id="p21" srsName="http://www.opengis.net/def/crs/EPSG/0/4326">
<gml:coordinates>45.67, 88.56 55.56,89.44</gml:coordinates> </gml:LineString >
```

Shapefile structure

- A Shapefile consists of a set of files with the same base name but different extensions.

1. **.shp (shape file)**:

   Contains the **geometry** of the features (points, lines, or polygons). This file holds the actual spatial data, which defines the shape and location of the geographic features.

2. **.shx (shape index file)**:

   Contains the **index** of the geometries in the .shp file. It allows for quick access to the shapes stored in the .shp file by storing the position of each shape's geometry.

3. **.dbf (attribute file)**:

   Contains the **attributes** associated with each feature. This file is in dBASE format and holds tabular data (like a database table) where each row corresponds to a feature in the .shp file, and each column represents an attribute of those features.

Shapefile structure

4. **.prj (projection file)** (optional):

   Contains the **coordinate system** and projection information for the Shapefile. This file describes the spatial reference system used for the spatial data in the Shapefile, allowing for proper alignment and scaling with other spatial datasets.

5. **.sbn / .sbx (spatial index files)** (optional):

   Contains spatial index information that helps in faster spatial queries and operations. These files are used to improve performance when dealing with large datasets.

6. **.xml (metadata file)** (optional):

   Contains **metadata** about the Shapefile, such as its source, accuracy, and purpose. This file is in XML format and provides additional information about the dataset.

Shapefile structure

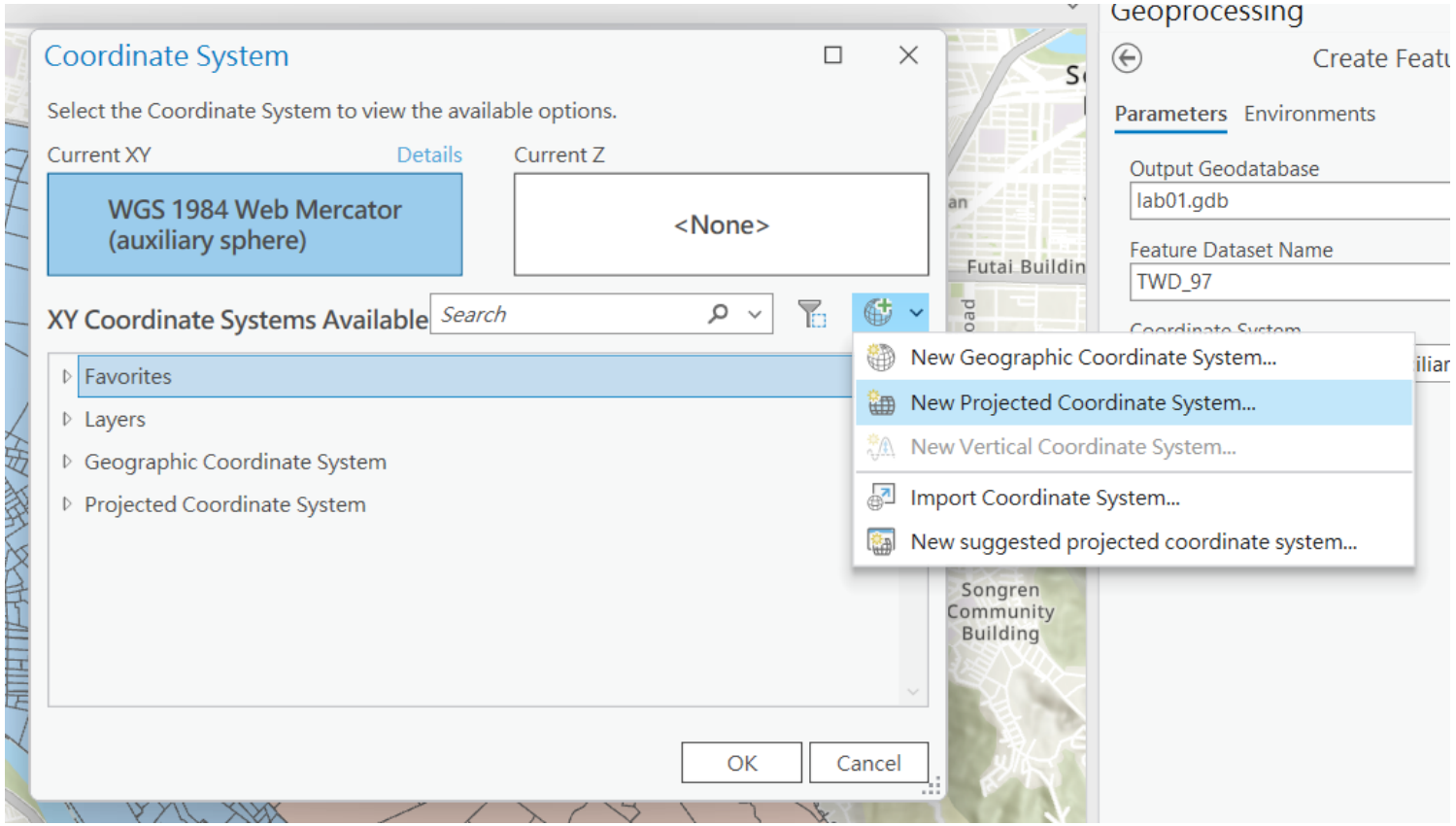
```
<Projected CRS: EPSG:3826>
Name: TWD97 / TM2 zone 121
Axis Info [cartesian]:
- X[east]: Easting (metre)
- Y[north]: Northing (metre)
Area of Use:
- name: Taiwan, Republic of China - between 120°E and 122°E, onshore and offshore - Taiwan Island.
- bounds: (119.99, 20.41, 122.06, 26.72)
Coordinate Operation:
- name: Taiwan 2-degree TM zone 121
- method: Transverse Mercator
Datum: Taiwan Datum 1997
- Ellipsoid: GRS 1980
- Prime Meridian: Greenwich
```

- Here is the codebase population data in Taiwan

	U_ID	CODEBASE	CODE1	CODE2	TOWN_ID	COUNTY_ID	X	Y	AREA	H_CNT	P_CNT	M_CNT	F_CNT	geometry
0	1972.0	A6310-0024-00	A6310-01-006	A6310-01	63000100	63000	310951.84060	2.775913e+06	362112.90727	14	37	18	19	POLYGON Z ((310568.684 2775912.720 0.000, 3105...
1	1973.0	A6311-0791-00	A6311-61-005	A6311-61	63000110	63000	300103.56005	2.776286e+06	17541.31869	9	21	10	11	POLYGON Z ((299986.213 2776330.686 0.000, 3000...
2	1974.0	A6311-0787-00	A6311-67-002	A6311-67	63000110	63000	302742.35826	2.776312e+06	3627.65319	48	94	48	46	POLYGON Z ((302752.204 2776365.558 0.000, 3027...
3	1975.0	A6311-0793-00	A6311-62-004	A6311-62	63000110	63000	302298.08171	2.776278e+06	15430.37397	131	352	168	184	POLYGON Z ((302336.695 2776362.841 0.000, 3023...
4	1976.0	A6311-0807-00	A6311-67-008	A6311-67	63000110	63000	302823.86029	2.776199e+06	52775.40011	0	0	0	0	POLYGON Z ((302717.351 2776356.819 0.000, 3027...

CRS settings in ArcGIS Pro

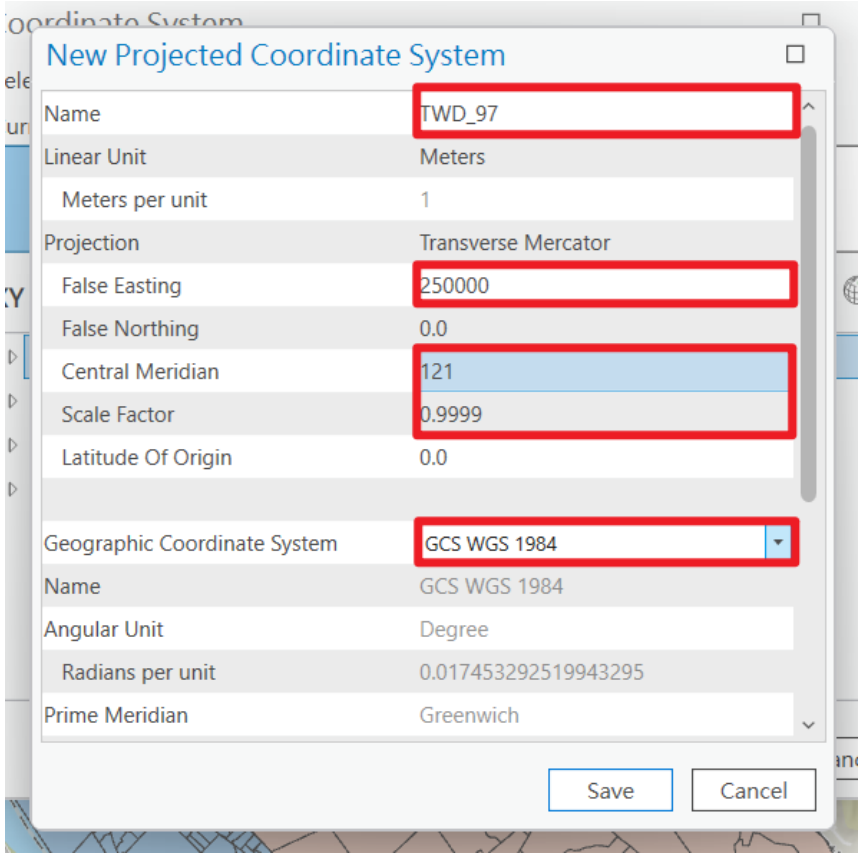
- Coordinate reference systems (CRS)



Thanks for 張自成 doing this slide

CRS settings in ArcGIS Pro

- Coordinate reference systems (CRS)



Custom Name

2-degree transverse Mercator's easting.

Slightly adjusting the size of the map along the central meridian to correct or reduce this distortion.

In TWD97, the reference ellipsoid used is GRS80. However, GRS80 is not directly available in ArcGIS Pro. Due to its similarity, we select the closest alternative, GCS_WGS_1984, for convenience.

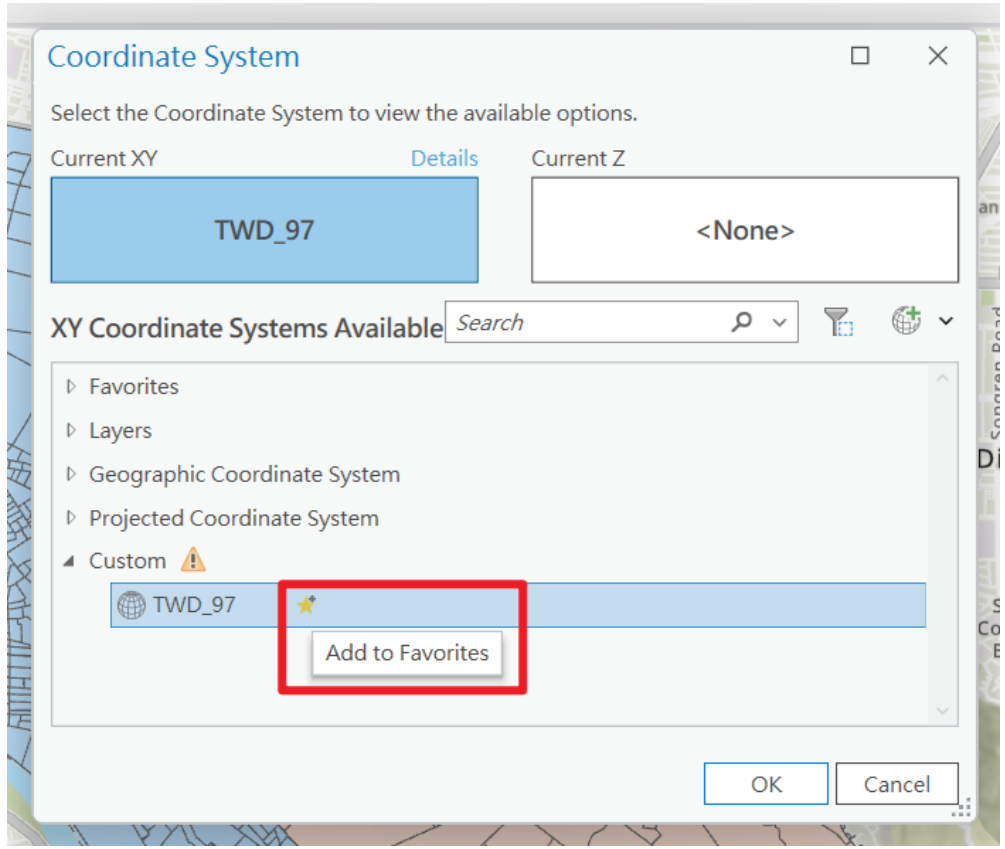
TWD basics

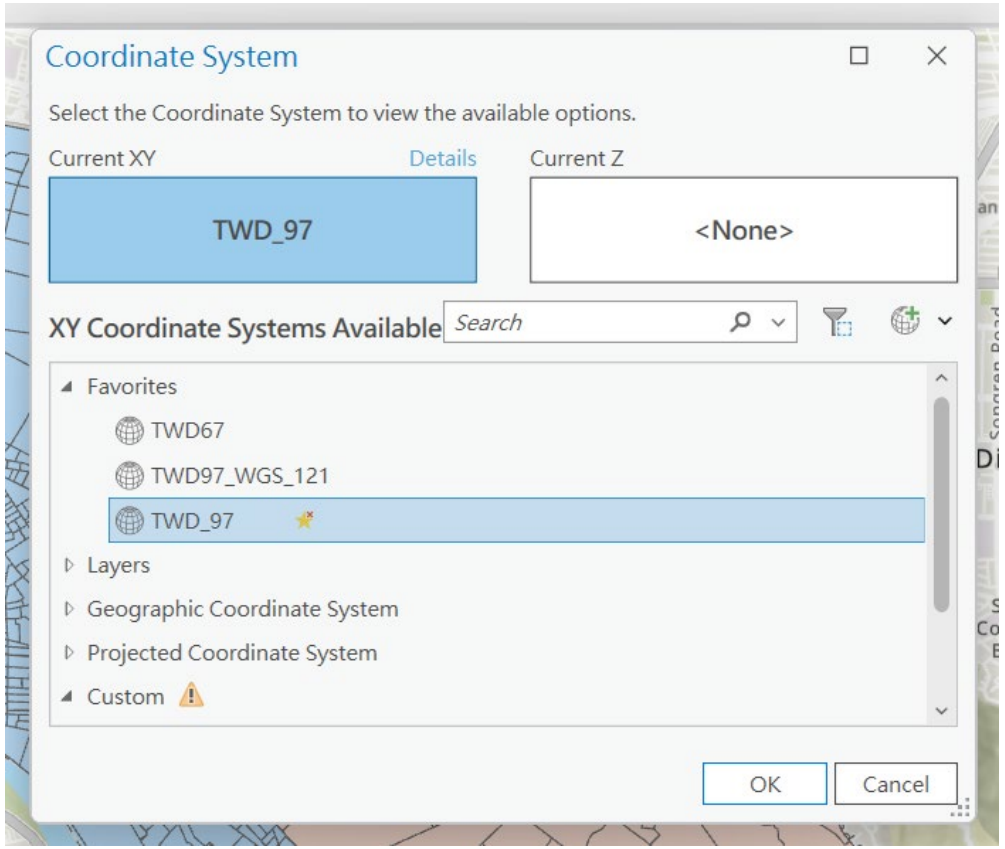
Latitude origin	0 degrees
Central meridian	121 degrees E (台灣本島, 東引), 119 degrees E (澎湖, 金門, 馬祖)
Scale factor	0.9999
False easting	250000 m
False northing	0 m

Thanks for 張自成 doing this slide

CRS settings in ArcGIS Pro

- Coordinate reference systems (CRS)





Thanks for 張自成 doing this slide

The End

Thank you for your attention!

Email: chchan@ntnu.edu.tw
Web: toodou.github.io